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A Robust Dynamic Region-Based Control Scheme for an Autonomous Underwater Vehicle

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Abstract- Intelligent control of an autonomous underwater vehicle (AUV) requires a control scheme which is robust to external perturbations. These perturbations are highly uncertain and can prevent the AUV from accomplishing its mission. A well-known robust control called sliding mode control (SMC) and its development have been introduced. However, it produces a chattering effect which requires more energy. To overcome this problem, this paper presents a novel robust dynamic region-based control scheme. An AUV needs to be able not only to track a moving target as a region but also to position itself inside the region. The proposed controller is developed based on an adaptive sliding mode scheme. An adaptive element is useful for the AUV to attenuate the effect of external disturbances and also the chattering effect. Additionally, the application of the dynamic-region concept can reduce the energy demand. Simulations are performed to illustrate the effectiveness of the proposed controller. Furthermore, a Lyapunov-like function is presented for stability analysis. It is demonstrated that the proposed controller work better then an adaptive sliding mode without the region boundary scheme and a fuzzy sliding mode controller.

KEYWORDS: Adaptive sliding-mode control; Robust control; Dynamic region based approach; Autonomous underwater vehicle

1. INTRODUCTION

It is well known that an underwater vehicle is the favored solution to be deployed in many undersea applications especially in the military field and the oil and gas industry. Therefore, it drives marine engineers and researchers to focus on improving the ability of the underwater vehicle particularly in regulation and tracking tasks. Among the control schemes which are adapted for Autonomous Underwater Vehicle (AUV), the Proportional-Derivative (PD) control plus gravity compensation (Takegaki and Arimoto, 1981) is the simplest set-point technique for controlling an AUV. However, the dynamics of an AUV depends on the subsea conditions and requires exact knowledge of the gravity and buoyancy forces. In fact, the underwater zone is highly non-linear. It is difficult to obtain the exact model of the gravitational and buoyancy forces which can prevent an AUV to stay at a certain point.

One known approach to counter this problem is an adaptive controller. This approach is one of the effective ways to deal with the parameter uncertainties of an AUV. The gain is automatically tuned as the system changes. Earlier work on AUV control using an adaptive controller can be found in Yuh et al. (1999); Antonelli and Chiaverini (1998); Fossen and Sagatun (1991a); Yuh (1990); Fossen and Sagatun (1991b); Slotine and Li (1987). As an extension of Fossen and Sagatun (1991), Antonelli proposed using an adaptive approach for an underwater vehicle with an onboard manipulator based on a quaternion attitude representation to deal with singularities if Euler angles are used and was experimentally validated on ODIN (Antonelli et al., 2001). Although an adaptive controller can solve the uncertainty problem, Sun and Cheah (2003) stated that the adaptive controller required a regressor vector of the dynamic model which includes the inertia matrix, Coriolis and centripetal force, hydrodynamic damping, gravity and buoyancy forces. Thus, the dynamic model to be updated by the adaptive law is very large. Motivated from the work by Arimoto (1996), Yarazel et al. (2002), Cheah et al. (2001) that was used for robot manipulators, Sun proposed using only the gravity term in the regressor and did not include the others. Contrary from Sun, Yuh and Nie (2000) proposed using a non

regressor-based adaptive control scheme for an underwater vehicle. As an extension of this work, Zhao et al. proposed combining the non regressor-based adaptive with a disturbance observer (DOB) in Zhao et al. (2004).

Another control method which is widely used for an AUV is sliding mode control (SMC). SMC is well known for its robustness against disturbances and uncertainty. However, the major drawback of this type of controller is the chattering effect. Thus, significant research has focused on eliminating or reducing the chattering effect. Soylu et al. (2008) proposed an adaptive concept to replace the switching term in conventional sliding mode control where it aims to minimize the chattering effect in the trajectory control of a remotely operated vehicle. Then, Bessa et al., (2010) used an adaptive fuzzy sliding mode controller to deal with the parameter uncertainties and external disturbance. To overcome the chattering effect, Bessa et al. designed boundary layers and it led to inferior tracking performance. The issue is resolved using an adaptive fuzzy algorithm for uncertainty/disturbance compensation. Sun et al. (2012) expanded the use of approach control by Soylu. In this work a kinematics/dynamics cascaded control system was integrated with a backstepping technique.

However, each method has its own disadvantages. For the adaptive SMC, it can reduce the chattering effect but it cannot reduce the energy demand. The use of fuzzy control in the SMC method requires many rules in order to achieve good performance. When more rules are applied, more energy will be required. It also reduces the robustness of the AUV. In the case of the backstepping approach, it causes a speed jump problem. According to Sun et al. (2012), the speed jump happens due to the velocity control law being directly related with the state error causing a large velocity with a big initial error condition.

In the case of reducing energy usage, Li et al. (2010) was successful in introducing an adaptive region tracking controller to overcome this weakness. Li proposed that instead of a point being used as the final target, it is better to use a region as the final target for energy saving purposes. This is due to the controller only being activated when the AUV is outside the region rather than always moving the

AUV to the point target in the conventional method. The proposed technique in Li et al. (2010) is also not limited for controlling a single AUV, the region control technique can also be utilized for a swarm of AUVs as reported in Hou et al. in (2009).

By utilising the advantages of each method, this paper proposes a robust dynamic region technique using an adaptive sliding-mode algorithm for an AUV. In this control concept, the desired target is specified as a moving region where the proposed controller is only activated when the AUV is outside the desired region. Due to the added adaptive term in the sliding mode controller, the chattering effect of ordinary sliding mode control is minimized. A Lyapunov-like function is presented for the stability analysis. Simulation results for an AUV with 6 degrees-of-freedom are presented to demonstrate the effectiveness of the proposed controller. The rest of the paper is organized as follows: Section 2 describes the kinematic and dynamic properties of an AUV. In Section 3, the sliding mode adaptive controller with region function formulation is explained. The stability analysis using a Lyapunov-like function is also given in this section. In Section 4, numerical simulation results are provided to demonstrate the performance of the proposed controller. Finally, concluding remarks are presented in Section 5.

2. KINEMATIC AND DYNAMIC MODEL OF AN AUV

A. Kinematic Model

The relationship between inertial and body-fixed vehicle velocity can be described using the Jacobian matrix $J(\eta_2)$ in the following form (Fossen, 1994)

$$\begin{bmatrix} \dot{\eta}_1 \\ \dot{\eta}_2 \end{bmatrix} = \begin{bmatrix} J_1(\eta_2) & 0_{3 \times 3} \\ 0_{3 \times 3} & J_2(\eta_2) \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \Leftrightarrow \dot{\eta} = J(\eta_2)v \quad (1)$$

where $\eta_1 = [x \ y \ z]^T \in \mathbb{R}^3$ and $\eta_2 = [\phi \ \theta \ \psi]^T \in \mathbb{R}^3$ denote the position and the orientation of the vehicle, respectively, expressed in the inertial-fixed frame. J_1 and J_2 are the transformation matrices expressed in terms of the Euler angles. The linear and angular velocity vectors, $v_1 =$

$[u \ v \ w]^T \in \mathbb{R}^3$ and $v_2 = [p \ q \ r]^T \in \mathbb{R}^3$, respectively, are described in terms of the body-fixed frame.

B. *Dynamic Model*

The dynamic equation of motion for an underwater vehicle has been previously reported in Fossen (1994) and can be expressed in closed form as

$$\tau = M\dot{v} + C(v)v + D(v)v + g(\eta) \quad (2)$$

where $v \in \mathbb{R}^6$ is the velocity state vector with respect to the body-fixed frame, M is the inertia matrix including the added mass term, $C(v)$ represents the matrix of the Coriolis and centripetal forces including the added mass term, $D(v)$ denotes the hydrodynamic damping and lift force, $g(\eta)$ is the restoring force and τ is the vector of generalized forces acting on the vehicle. The dynamic equation in (2) preserves the following properties (Fossen, 1994) :

Property 1: The inertia matrix M is symmetric and positive definite such that $M = M^T > 0$.

Property 2: $C(v)$ is the skew-symmetric matrix such that $C(v) = -C^T(v)$.

Property 3: The hydrodynamic damping matrix $D(v)$ is positive definite, i.e.: $D(v) = D^T(v) > 0$.

Underwater vehicle dynamics are dominated by hydrodynamic loads and it is difficult to accurately measure the hydrodynamic loads for an underwater vehicle, thus the dynamics are not exactly known.

Let $f(\cdot) = J^{-T}\tau$, then the system dynamics can be written as the sum of an estimated dynamics $\hat{f}(\cdot)$, and unknown dynamics $\tilde{f}(\cdot)$. In other words, $f(\cdot)$ can be represented as

$$f(\cdot) = \hat{f}(\cdot) + \tilde{f}(\cdot) = M_\eta \ddot{\eta} + C_\eta(v, \eta) \dot{\eta} + D_\eta(v, \eta) \dot{\eta} + g_\eta(\eta) \quad (3)$$

where $M_\eta = J^{-T}MJ^{-1}$, $C_\eta(v, \eta) = J^{-T}[C - MJ^{-1}J]J^{-1}$, $D_\eta(v, \eta) = J^{-T}DJ^{-1}$ and $g_\eta = J^{-T}g$.

The estimated dynamics vector in (3) is defined as

$$\hat{f}(\cdot) = \hat{M}_\eta \ddot{\eta} + \hat{C}_\eta(v, \eta) \dot{\eta} + \hat{D}_\eta(v, \eta) \dot{\eta} + \hat{g}_\eta(\eta) \quad (4)$$

while the unknown dynamics vector is defined as

$$\tilde{f}(\cdot) = \tilde{M}_\eta \ddot{\eta} + \tilde{C}_\eta(v, \eta) \dot{\eta} + \tilde{D}_\eta(v, \eta) \dot{\eta} + \tilde{g}_\eta(\eta) + d \quad (5)$$

where $\tilde{M}_\eta = M_\eta - \hat{M}_\eta$, $\tilde{C}_\eta = C_\eta - \hat{C}_\eta$, $\tilde{D}_\eta = D_\eta - \hat{D}_\eta$ and $\tilde{g}_\eta = g_\eta - \hat{g}_\eta$. The vector d is added as an external disturbance force considering the current effect v_d that acts on the vehicle (Antonelli, 2007). $\tilde{f}(\cdot)$ is also referred to as a lumped uncertainty vector (Lin et al., 2002).

Assumption 1 : The nonlinear lumped uncertainty vector, given in equation (5) and its time derivative are bounded.

3. ADAPTIVE SLIDING MODE CONTROL WITH REGIONAL FORMULATION

A. Region Boundary Control Law

In the region boundary-based control law, the desired moving target is specified by at least two sub-regions intersecting at the same point. The inner sub-region acts a repulsive region while the outer sub-region acts as an attractive region. The regulation control concept presented in Ismail and Dunnigan (2011a) was extended for coordination control of multiple AUVs (Ismail and Dunnigan, 2011b). The region boundary concept can be generalized to a region control law if the inner sub-region is defined to be arbitrarily small (Sun and Cheah, 2009). Thus, a proposed robust tracking control for an AUV subject to regional formulation is presented as follows.

First, a dynamic region of specific shape is defined and this can be viewed as a global objective of the proposed control law. Define a desired region as the following inequality equation:

$$\mathcal{F}(\delta\eta) \leq 0 \quad (6)$$

where, $\delta\eta = (\eta - \eta_d) \in \mathbb{R}^6$ are the continuous first partial derivatives of the dynamic region, whilst, $\eta_d(t)$ is the time-varying reference point inside the region shape. It is assumed that $\eta_d(t)$ is a bounded function of time.

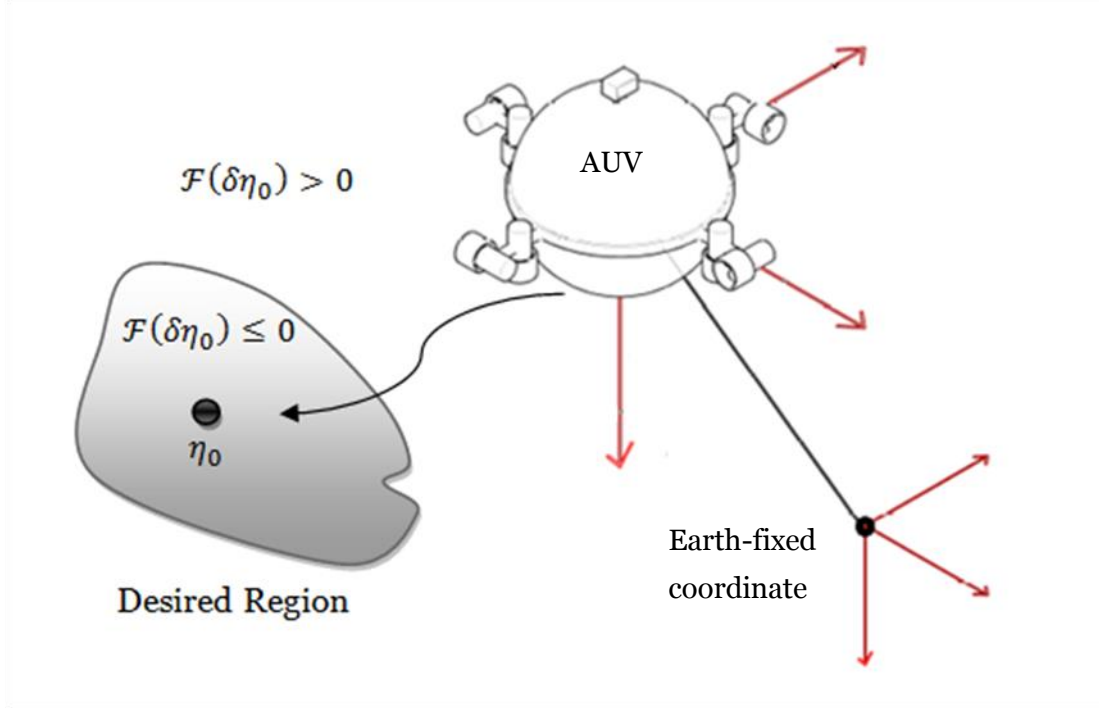


Figure 1: Definition of desired region - $\mathcal{F}(\delta\eta) \leq 0$

For example if, $\mathcal{F}(\delta\eta) = (x \ y)^T \in \mathbb{R}^2$, a desired region can be specified as follows

$$\mathcal{F}(\delta\eta) = (x - x_o)^2 + (y - y_o)^2 - r^2 \leq 0 \quad (7)$$

where $\eta_o = (x_o \ y_o)^T$ is the center of the desired region and r is the radius of the region.

The potential energy function for the desired region is as follows:

$$P_p(\delta\eta) \triangleq \begin{cases} 0, & \mathcal{F}(\delta\eta) \leq 0 \\ \frac{k_p}{2} \mathcal{F}^2(\delta\eta), & \mathcal{F}(\delta\eta) > 0 \end{cases} \quad (8)$$

where k_p is a positive scalar. An illustration for the potential energy for the desired equation is shown in Figure 2.

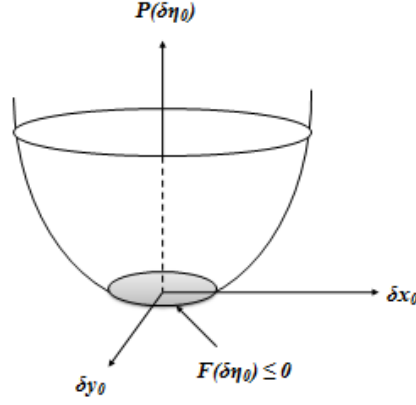


Figure 2: Potential energy function

Partially differentiating equation (8) with respect to $\partial \eta$ gives

$$\left(\frac{\partial P_p(\partial \eta)}{\partial \eta} \right)^T = k_p \max(0, \mathcal{F}(\delta \eta)) \left(\frac{\partial \mathcal{F}(\delta \eta)}{\partial \eta} \right)^T \quad (9)$$

Now, let (9) be represented as a region error $\Delta \xi$ in the following form

$$\Delta \xi = \max(0, \mathcal{F}(\delta \eta)) \left(\frac{\partial \mathcal{F}(\delta \eta)}{\partial \eta} \right)^T \quad (10)$$

Note that the product rule can be used to obtain the derivatives of products for two or more regional functions. When the AUV is outside the desired region, the control force $\Delta \xi$ described by (9) is activated to attract the AUV towards the desired region. When the AUV is inside the desired region, then the control force is zero or $\Delta \xi = 0$.

B. Sliding Mode Adaptive Control with Dynamics Region

In order to minimize the discontinuous term as well as the chattering problem, an adaptive term is added to the control law as follows

$$\tau = \tau_{eq} + \tau_{ad} \quad (11)$$

where, τ_{eq} symbolizes the equivalent control and τ_{ad} is the adaptive term.

The model of equivalent control law (τ_{eq}) can be derived by assuming that the motion is constrained to the sliding manifold. The sliding manifold is defined as

$$s = v - v_r \quad (12)$$

where, $v_r = J^{-1}(\dot{\eta}_d - \delta\eta) - J^{-1}\Delta\xi$ is the reference vector.

Differentiating the sliding manifold, yields,

$$\dot{s} = \dot{v} - \dot{v}_r \quad (13)$$

Multiplying both sides of (13) by the inertia matrix \hat{M} and substituting (2) into the resulting equation gives

$$\hat{M}\dot{s} = \tau_{eq} - (\hat{M}\dot{v}_r + \hat{C}(v)v + \hat{D}(v)v + \hat{g}(\eta)) \quad (14)$$

When the system is operating on the sliding surface, equation (14) is equal to zero, yielding an equivalent control

$$\tau_{eq} = \hat{M}\dot{v}_r + \hat{C}(v)v + \hat{D}(v)v + \hat{g}(\eta) \quad (15)$$

where (15) can also be represented in the inertial reference frame as follows

$$\tau_{eq} = J^T \hat{f}_r(\eta, v, \dot{v}_r) \quad (16)$$

If the adaptive concept is substituted to the ordinary sliding mode control, τ_{ad} is defined as

$$\tau_{ad} = J^T \tilde{f}_{est} - Ks - J^T(\eta)\Delta\xi \quad (17)$$

K is the gain value of the sliding surface. Then, the estimation of the lumped uncertainty vector (\tilde{f}_{est}) is given as

$$\dot{\tilde{f}}_{est} = -J^{-T}\Gamma s \quad (18)$$

where Γ is a positive definite diagonal constant design matrix that determines the rate of adaptation.

Therefore, the proposed sliding-mode adaptive control law with region formulation can be written as

$$\tau = J^T(\hat{f}_r + \tilde{f}_{est}) - Ks - J^T(\eta)\Delta\xi \quad (19)$$

Assumption 2: The following inequality is assumed to hold

$$s^T Ks \geq \left| \dot{\tilde{f}}^T \Gamma^{-1} w \right| \text{ only when } \dot{\tilde{f}}^T \Gamma^{-1} w < 0$$

Theorem 1: Consider the nonlinear dynamical system described by (2) with Assumptions 1 and 2. If the region error formulation and proposed control law are expressed as (10) and (19), respectively, then the asymptotic tracking result for the closed-loop control system is guaranteed.

Proof: Define a Lyapunov-like function as

$$V = \frac{1}{2} s^T M s + w^T J \Gamma^{-1} J^T w + P_p(\delta\eta) \quad (20)$$

where $w = \tilde{f}_{est}(\cdot) - \tilde{f}(\cdot)$ is the difference vector between the estimated lumped uncertainty vector and the exact lumped uncertainty vector. $\tilde{f}(\cdot)$ and $\dot{\tilde{f}}_{est}$ are defined in (5) and (18) respectively.

Differentiating (20) with respect to time yields

$$\dot{V} = s^T M \dot{s} + \dot{w}^T J \Gamma^{-1} J^T w + (\delta\dot{\eta})^T k_p \max(0, \mathcal{F}(\delta\eta)) \left(\frac{\partial \mathcal{F}(\delta\eta)}{\partial \eta} \right)^T \quad (21)$$

Substituting (2) and (12) into (21) yields

$$\dot{V} = s^T (\tau - \tau_r) + \dot{w}^T J \Gamma^{-1} J^T w + (\delta\dot{\eta})^T k_p \max(0, \mathcal{F}(\delta\eta)) \left(\frac{\partial \mathcal{F}(\delta\eta)}{\partial \eta} \right)^T \quad (22)$$

where

$$\tau_r = J^T \dot{f}_r = M \dot{v}_r + C v_r + D v + g \quad (23)$$

Substituting equation (19) into equation (22)

$$\begin{aligned}\dot{V} = & s^T(J^T w - J^T(\eta)\Delta\xi - Ks) + \dot{w}^T J\Gamma^{-1}J^T w \\ & + (\delta\dot{\eta})^T k_p \max(0, \mathcal{F}(\delta\eta)) \left(\frac{\partial \mathcal{F}(\delta\eta)}{\partial \eta}\right)^T\end{aligned}\quad (24)$$

Substituting the adaptive law in (17) into (24) gives

$$\dot{V} = -s^T K s - \dot{\hat{f}}^T J\Gamma^{-1}J^T w - \Delta\xi^T \Delta\xi \quad (25)$$

It can be stated that

$$\dot{V} \leq -s^T K s - \dot{\hat{f}}^T J\Gamma^{-1}J^T w - \Delta\xi^T \Delta\xi \leq 0 \quad (26)$$

The inequality given in (26) implies that the system trajectories will converge to the sliding manifold $s = 0$, from any nonzero initial error. However, the inequality alone cannot imply that $V \rightarrow 0$ as $t \rightarrow \infty$, which means it cannot prove that the trajectories will always converge to the desired value in finite time. Barbalat's Lemma can be used to solve this problem. Since V is lower bounded ($V \geq 0$), \dot{V} is negative semi-definite ($\dot{V} \leq 0$), and \ddot{V} is bounded, then $\dot{V} \rightarrow 0$ as $t \rightarrow \infty$. Thus, the convergence of $\Delta\xi$ to zero implies that $\mathcal{F}(\delta\eta) \leq 0$. Therefore, η converges to the moving desired region $\mathcal{F}(\delta\eta) \leq 0$ and $\dot{\eta}$ converges to $\dot{\eta}_d$ as $t \rightarrow \infty$.

4. SIMULATION RESULTS

This section shows simulation results to assess the effectiveness of the proposed controller against external disturbances. The type of autonomous underwater vehicle (AUV) which is chosen as a vehicle model is an ODIN with 6-DOFs given in Choi et al. (1993). Numerical values for the matrices of the vehicle dynamic equations are available in Podder and Sarkar (2001).

For the first case, a sliding mode adaptive control with region boundary technique is employed as a proposed controller. Then, its results are compared with an adaptive sliding mode control without the region technique and a fuzzy sliding mode control method. In all simulations, the ODIN vehicle is

requires to track a pre-defined trajectory (indicated by the red color) as well as converge to the desired region (indicated by the green cross-section color). For the proposed controller, the value of K is set as $[80 \ 80 \ 80 \ 1 \ 1 \ 1]^T$ while Γ is set as $[0.01 \ 0.01 \ 0.01 \ 1 \ 1 \ 1]^T$. In the simulations using an adaptive sliding mode without the region technique, the value of K and Γ are assigned as $[400 \ 400 \ 400 \ 1 \ 1 \ 1]^T$ and $[150 \ 150 \ 150 \ 1 \ 1 \ 1]^T$, respectively. Furthermore, the initial or starting point is at $[1.5 \ 0 \ -1.2]^T$ m which is signed with a "x" mark. The illustration can be seen in Fig. 3.

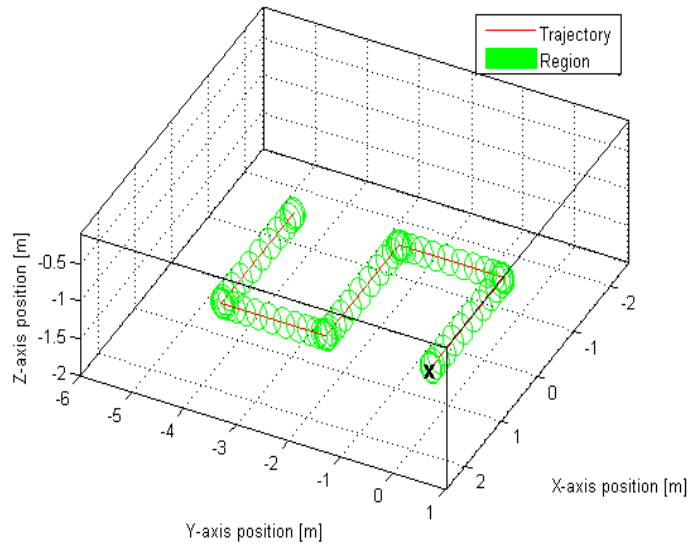


Fig 3. Illustration of simulation conditions

The following inequality functions are defined for a spherical region as,

$$\mathcal{F}(\delta\eta_1) = (x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 \leq \kappa_r^2 \quad (29)$$

where, κ_r is a region radius and its value is set to $\kappa_r = 0.2$ m.

In the middle of accomplishing a task, a deterministic value of external disturbance which is assumed as an ocean current velocity disturbs the AUV's movement. This perturbation exists between 50 s to 80 s of the time and acts on the y axis. Its value is given as $v_d = 0.04 \frac{m}{s}$. Note that the presence of the ocean current v_d has been considered through the dynamic model of the form (5) (Antonelli, 2007).

For the result, Fig. 4 shows a 3D movement of the AUV using adaptive sliding mode control with the

region boundary scheme. Before it is disturbed by ocean current, the AUV could track the trajectory precisely. However, after the perturbation, the AUV moves from its trajectory although it is still in the boundary area. The AUV then comes back to the middle of region when the perturbation is removed. Moreover, the AUV's position in each axis is shown in Fig. 5 for the X-axis, Fig. 6 for the Y-axis, and Fig. 7 for the Z-axis. From Fig. 6, it can be seen that the AUV took 50 s to return to the middle position. As stated before, the perturbation acted on the Y-axis. Thus, the X and Z axes were not influenced by the ocean current. And the errors in the X-axis and Z-axis were small. In contrast, the Y-axis error was bigger, especially between 50 s to 80 s. The error value is displayed in Fig. 8.

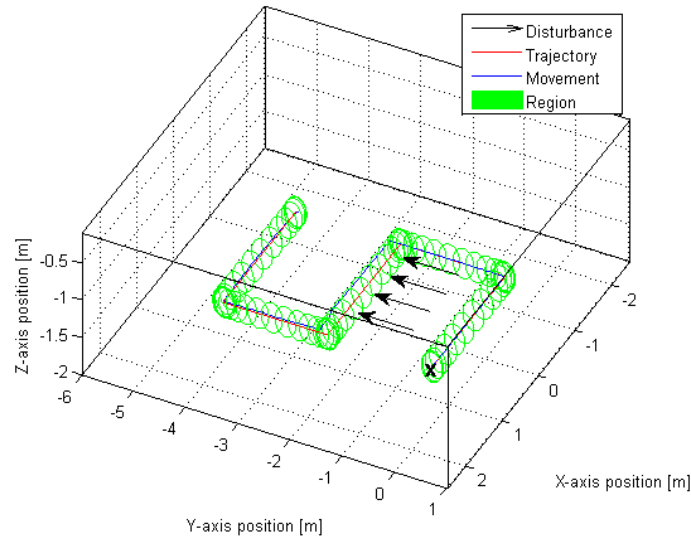


Figure 4. 3D View of proposed controller

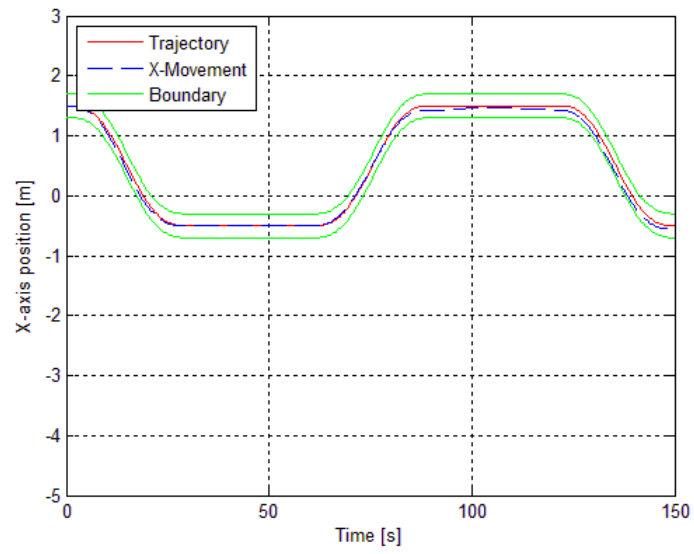


Figure 5. X-axis position when using proposed controller

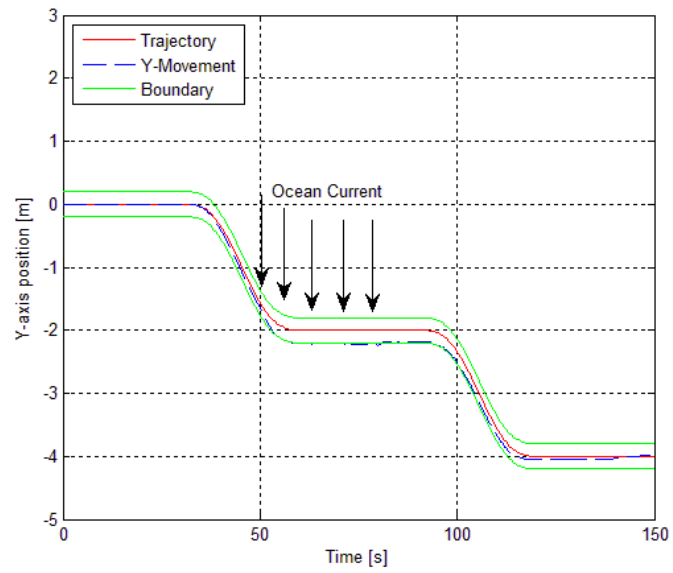


Figure 6. Y-axis position when using proposed controller

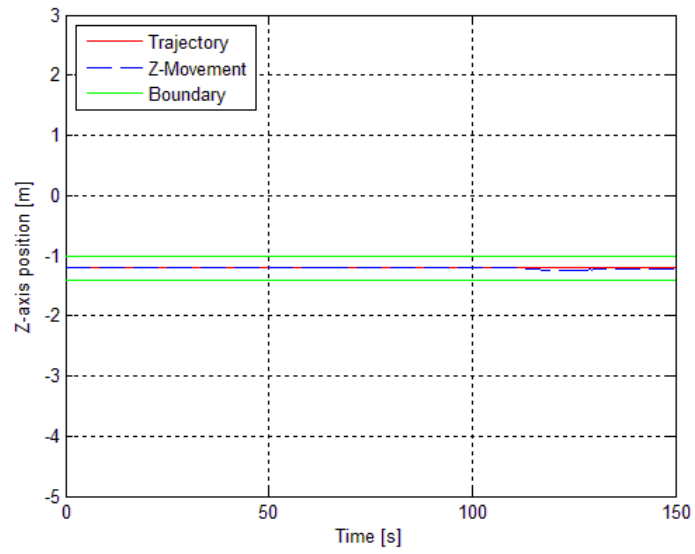


Figure 7. Z-axis position when using proposed controller

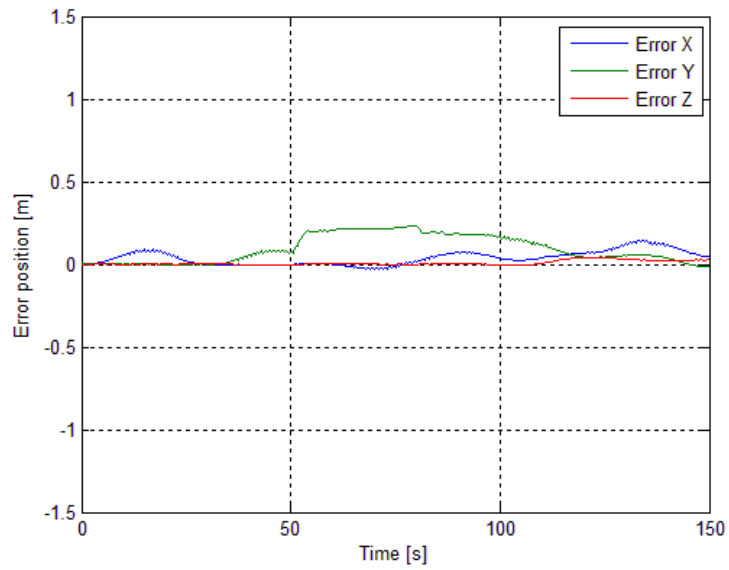


Figure 8. Error value when using proposed controller

For the case of the adaptive sliding mode control without the region technique, the 3D view movement result is shown in Fig. 9. As for case 1, the AUV can track the pre-defined trajectory between of 0 s to 50 s. After that, its performance was disturbed by the ocean current for about 30 s. Compared to the first case, the AUV does not follow the pre-defined trajectory as precisely. The

AUV's position in each axis is shown in Fig. 10 - Fig. 12. The error values for three axes are depicted in Fig. 13. The errors before the disturbance at 50 s are small for all axes. However after the disturbance is introduced, the error in the Y-axis increases and remains the same until the end of task. Therefore, the AUV does not come back to its trajectory although the perturbation has been removed.

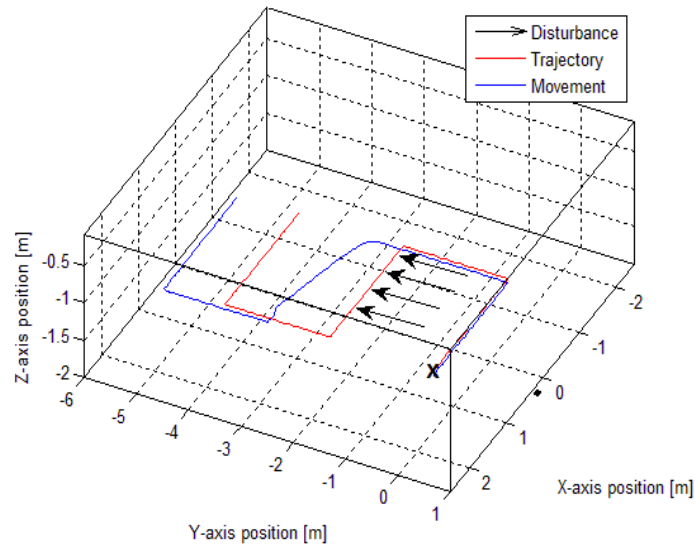


Figure 9. 3D View of adaptive SMC without the region method

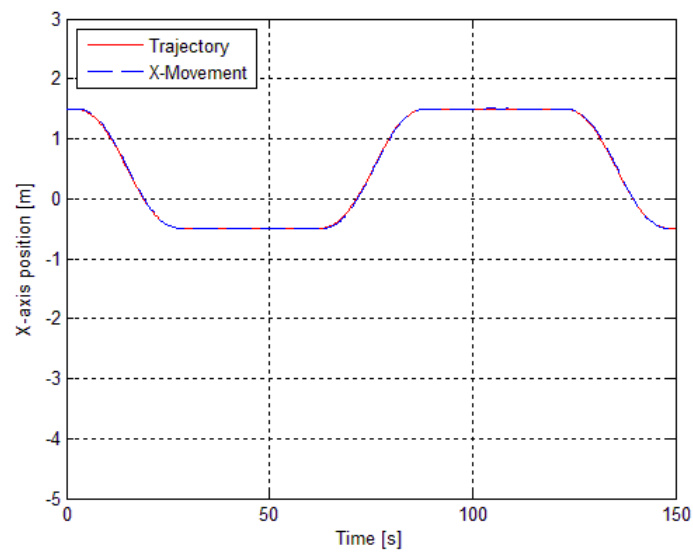


Figure 10. X-axis position when using adaptive SMC without the region method

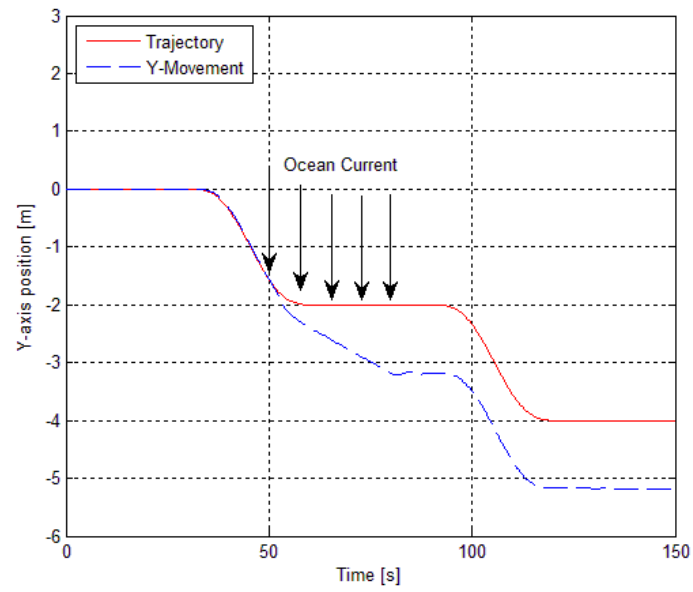


Figure 11. Y-axis position when using adaptive SMC without the region method

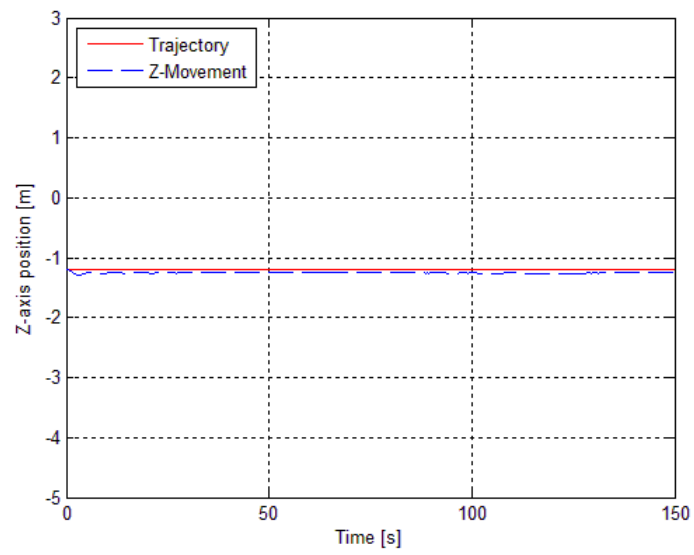


Figure 12. Z-axis position when using adaptive SMC without the region method

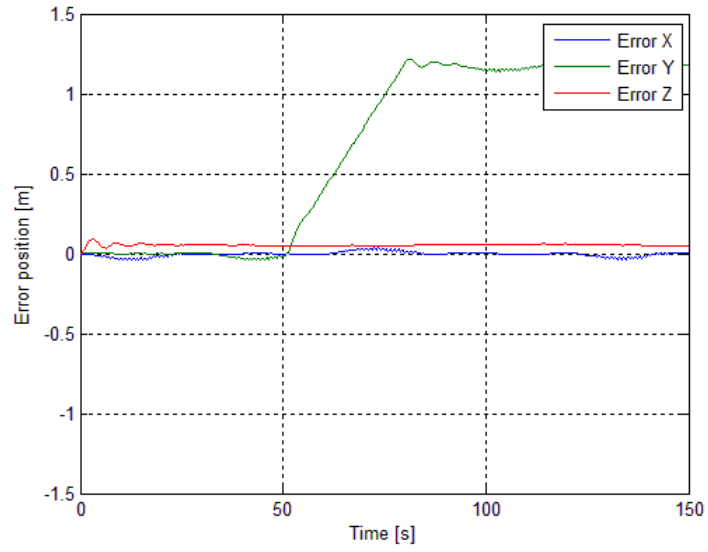


Figure 13. Error value when using adaptive SMC without the region method

The results for the third and final case using the fuzzy SMC controller are similar to the second case. Before the perturbation is introduced, the AUV can track the trajectory well. Once the ocean current disturbance is introduced, its movement is disturbed. The AUV moves far from its desired position and also does not return when the perturbation is removed. The 3D view result can be seen in Fig. 16. Compared to the second case, the fuzzy SMC has a larger error in the X-axis (110 s to 125 s). The Y-axis error was almost the same, while the Z-axis error was smaller than the second case. These are illustrated in Fig. 17 and Fig. 18. The errors in X, Y and Z-axes are depicted in Fig. 19. The Y-axis has the biggest error, followed by the X-axis and then the Z-axis. The forces in the Z-axis remain the same for the entire time.

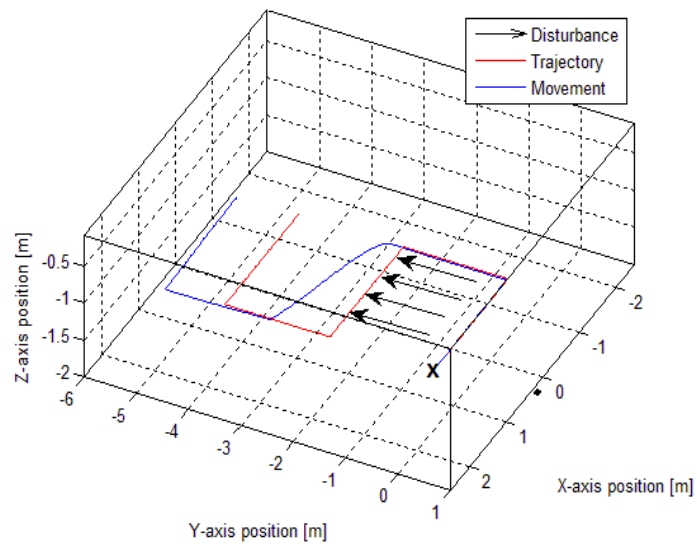


Figure 16. 3D View of fuzzy SMC

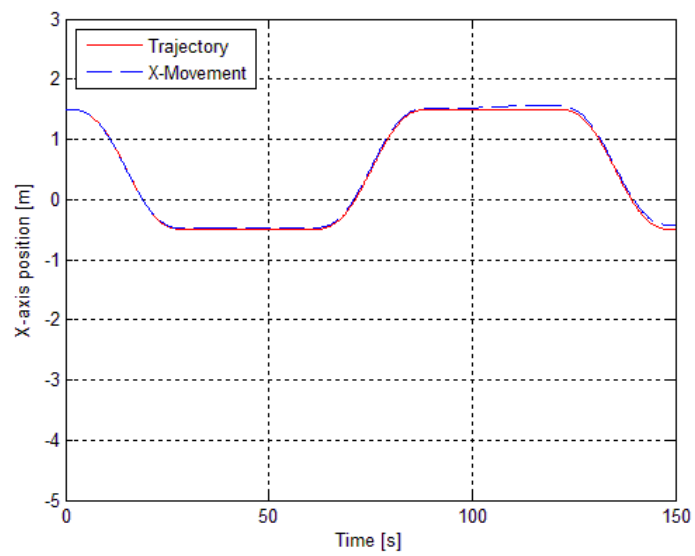


Figure 17. X-axis position when using fuzzy SMC

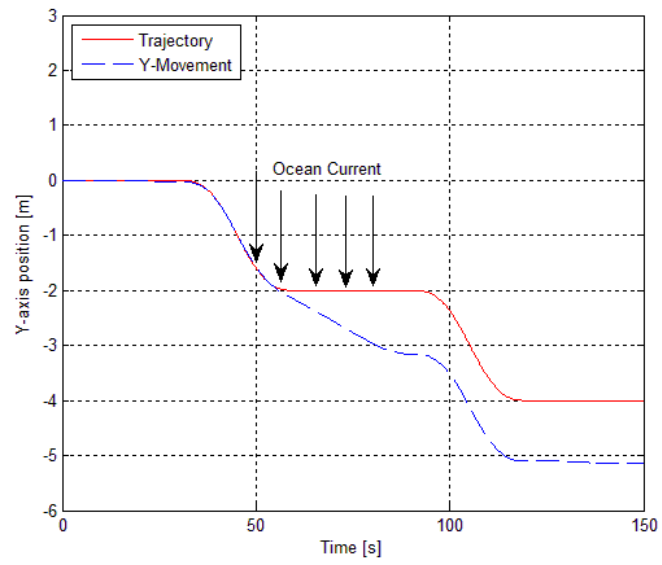


Figure 16. Y-axis position when using fuzzy SMC

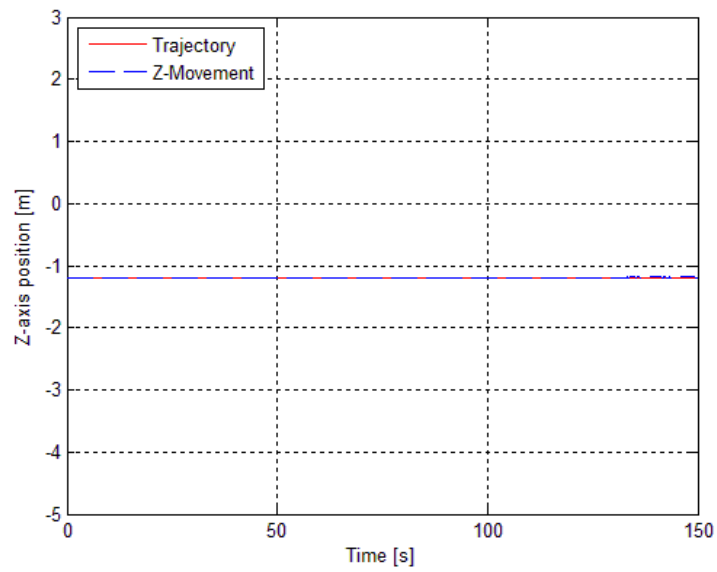


Figure 17. Z-axis position when using fuzzy SMC

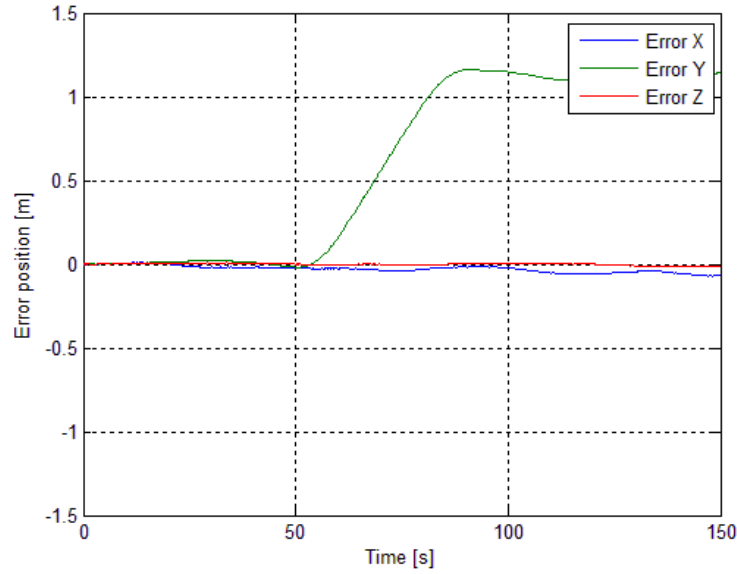


Figure 18. Error value when using fuzzy SMC

The energy demands after accomplishing a mission are divided into two types, force and moment. The result of force is shown in Fig. 19. Fig. 19 (a) shows that forces for proposed controller when the AUV is not disturbed by perturbation are around 0 N both in X, Y and Z axes. However from 51 s to 107 s and from 130 s to 137 s, more forces are spent to keep the AUV inside the region. The forces in the second case are shown in Fig. 19 (b). This figure depicts that the force in the Z-axis is overshoot from 0 N to 37 N in the beginning. Then its value reduces to around 15 N and continues to oscillate around 20 N to 25 N. More forces are required between 50 s to 123 s in the Y-axis and the forces keep oscillate for the entire time in the X-axis. While in the third case, the force in the Z-axis oscillates between 20 N to 25 N from the beginning to the end of mission. The forces in X and Y-axes oscillate tightly for the entire time. The forces for final case are shown in Fig. 19 (c).

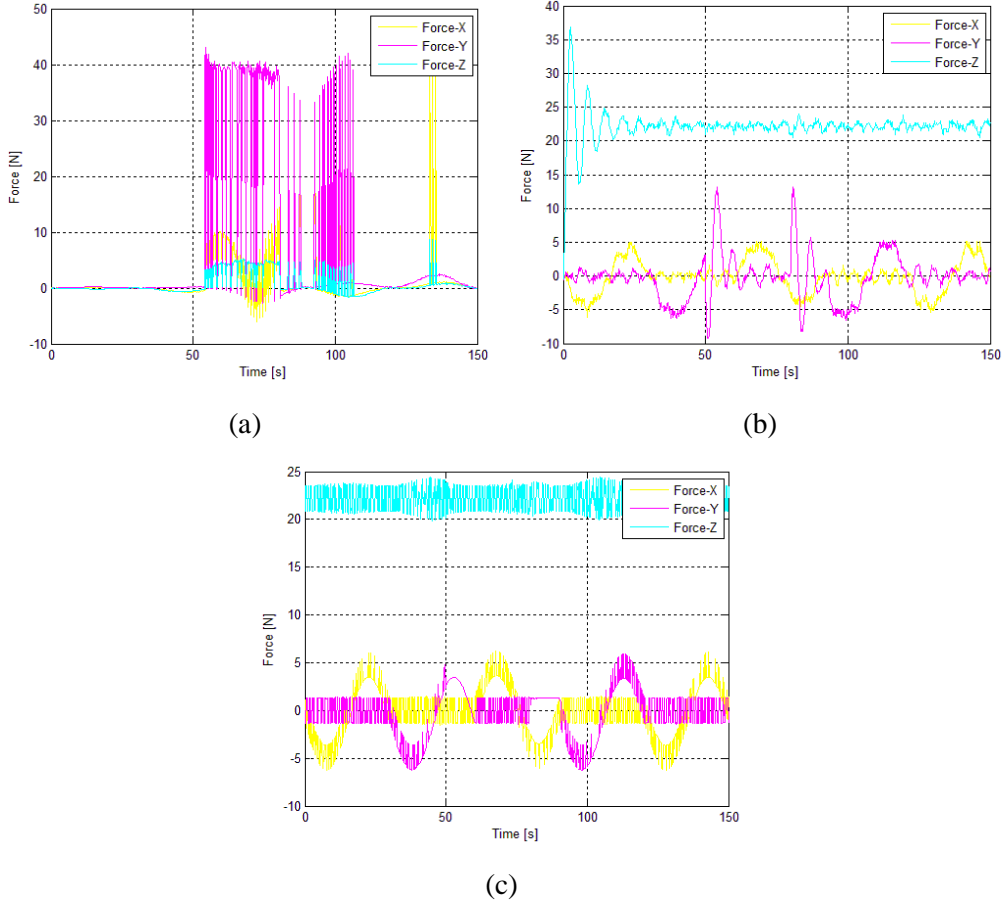


Figure 19. Required force

(a) proposed controller, (b) adaptive SMC without the region scheme and (c) fuzzy SMC

Meanwhile, the moment spent of each method is shown in Fig. 20. The results of moment when using proposed controller are depicted in Fig. 20 (a). Before the ocean current disturbance is introduced, the value of moment in ϕ , θ and ψ are around ± 0.01 Nm. Then its value reach the peak at 0.015 Nm before reduce to -0.04 Nm in the end of mission. Fig. 20 (b) shows the results of moment in the second case. The moment of ϕ oscillates from the beginning and tends to increase in positive value. Similarly to the moments of θ and ψ where they also oscillate for the entire time. However, the moment of θ tends to decrease in negative value, whilst the value of ψ -moment remains at about ± 0.01 Nm. The results in the third case when using fuzzy SMC are shown in Fig. 20 (c). The moments in all axes are oscillated for the entire time at around ± 1.3 Nm.

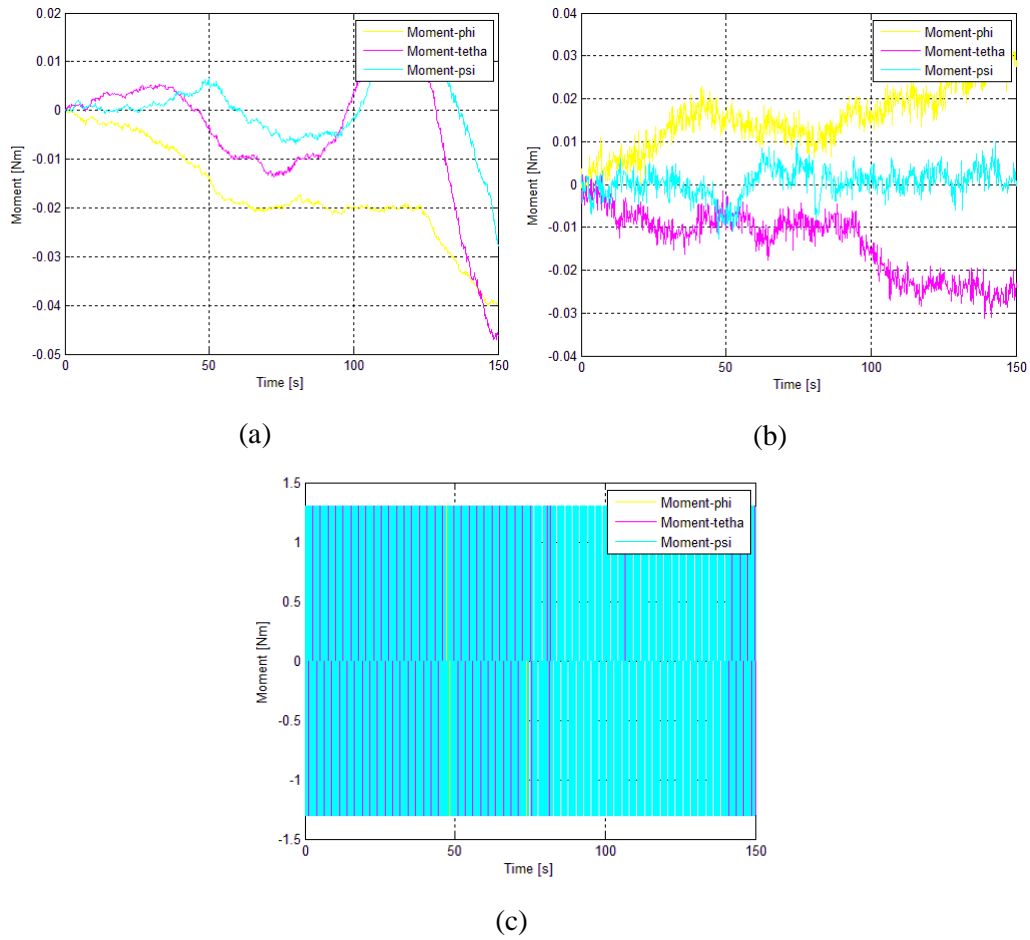


Figure 20. Required moment

(a) proposed controller, (b) adaptive SMC without the region scheme and (c) for fuzzy SMC

Table 1 shows the comparison between the required energy for three control methods in the exact value. The energy in each case is calculated by a norm formula of forces and moments for the entire time. From the results, it can be seen that the proposed controller required the least energy (both forces and moment values) compared to the two other controllers. Note that adaptive SMC without the region technique and fuzzy SMC require high control forces.

Table 1. Energy Consumption

Control Force/Moment	Proposed Controller	Adaptive SMC without Region	Fuzzy SMC
Force (N)	576.6	671.0	612.7
Moment (Nm)	0.6	0.67	45.7

The propulsion from the eight thrusters of ODIN can be obtained by considering the total energy demand from following formula,

$$\tau = EF_{th} \quad (30)$$

where τ is given in Eqn. 19. E denote the thruster configuration matrix, while F_{th} is the vector of thruster forces. To obtain the total propulsion (F_{th}) from the thrusters, it is necessary to obtain the inverse of E which is then multiplied by τ . The value of E is equal to,

$$E = \begin{bmatrix} c & -c & -c & c & 0 & 0 & 0 & 0 \\ c & c & -c & -c & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & -1 & -1 & -1 \\ 0 & 0 & 0 & 0 & Rc & Rc & -Rc & -Rc \\ 0 & 0 & 0 & 0 & Rc & -Rc & -Rc & Rc \\ R_z & -R_z & R_z & -R_z & 0 & 0 & 0 & 0 \end{bmatrix} \quad (31)$$

where $c = \sin \frac{1}{4}\pi$, $R = 0.381$ m and $R_z = 0.508$ m. R represent the distance from the centre of the vehicle to the centre of the vertical thrusters while R_z is distance from centre of vehicle to centre of horizontal thrusters (Podder and Sarkar, 2001). The results of thrusters' propulsion are shown in Fig. 21 for the proposed controller, Fig. 22 for the adaptive SMC without the region scheme and Fig. 23 for fuzzy SMC, respectively. The thrusters were only activated when the AUV moved from the predefined trajectory. Thrusters 1 to 4 were more active then thrusters 5 to 8 in proposed controller. This happened after the ocean current disturbance influenced the AUV. However, all thrusters were active in all the time for the adaptive SMC without the region boundary scheme and the fuzzy SMC. In these cases, thrusters 1 to 4 are active in the certain value at around ± 5 N, while thrusters 5 to 8 are active at around 5 to 10 N.

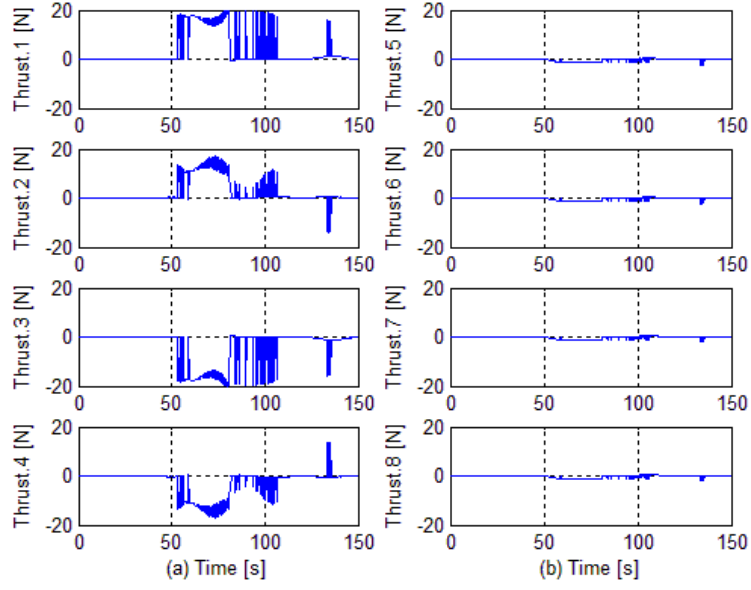


Figure 21. Thruster propulsion for proposed controller

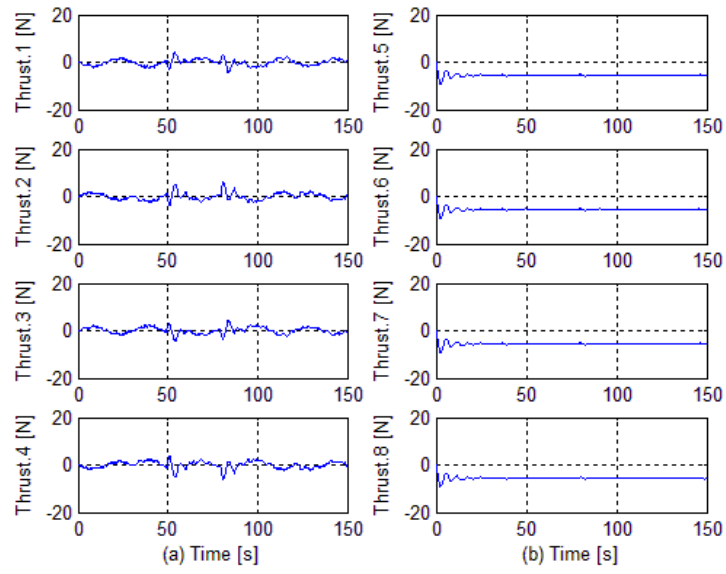


Figure 22. Thruster propulsion for adaptive SMC without region scheme

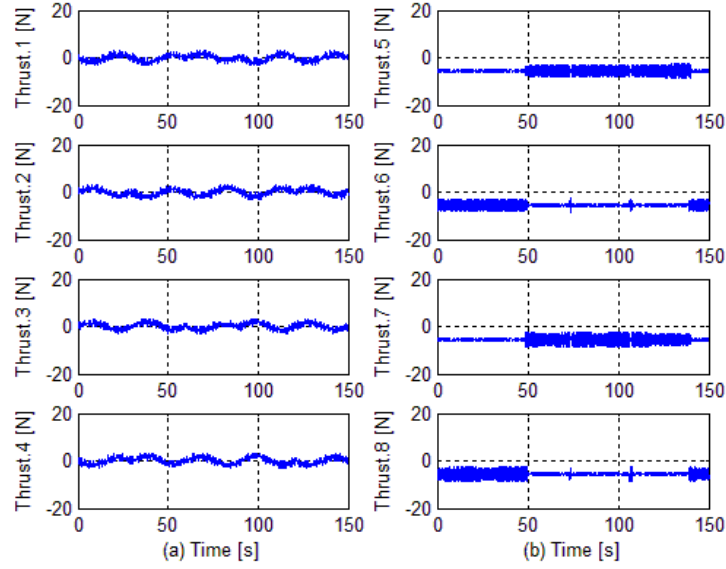


Figure 23. Thruster propulsion for fuzzy SMC

5. CONCLUSION

This paper proposed a new robust controller based on a region dynamic scheme for an autonomous underwater vehicle. By using this new control technique, the AUV was able to track a given underwater position trajectory with an external ocean current disturbance. Simulation results were presented to demonstrate the performance of the proposed tracking controller and its results were shown in Section IV. In terms of stability, a Lyapunov-like function is used to analyze its robustness. Compared to the adaptive SMC without the region method and the fuzzy SMC, the proposed controller minimized the chattering effect. The fuzzy SMC has the significant issue of it being difficult to determine appropriate rules to obtain good results. In addition, the proposed controller can reduce about 15.4 % for the force consumption and 10.4 % for the moment consumption compared to the other two methods.

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